RECENT CHANGES IN LAKE ERIE (NORTH SHORE) PHYTOPLANKTON:

CUMULATIVE IMPACTS OF PHOSPHORUS LOADING REDUCTIONS AND THE ZEBRA MUSSEL INTRODUCTION

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Note: All references to Ministry of Environment in this report should read Ministry of Environment and Energy.

ABSTRACT

Analyses of phytoplankton samples collected weekly and year-round at municipal water supply intakes in Lake Erie have shown a response to long-term changes in phosphorus loading and the more recent invasion of zebra mussels. Total phytoplankton densities in the western basin of Lake Erie declined from about 5000 Areal Standard Units (A.S.U.)/mL during the late 1960s to less than 1000 A.S.U./mL by the mid-1980s and coincided with declines in total phosphorus inputs to the western basin of about 50%. Similar declines were not observed at sites in the central and eastern basins; however, a further dramatic decline (>90%) at all four Lake Erie sites during 1988-1990 coincided with the invasion of the lake by zebra mussels (Dreissena polymorpha). Similar declines in phytoplankton were not observed at reference sites in southern Lake Huron, where zebra mussels were not abundant. In the western basin, chlorophyll a concentrations of <1 μg/L for most of the April to September period of 1991 were typical of oligotrophic areas of the upper Great Lakes. The proportional representation by the dominant classes of algae remained unchanged after the zebra mussel invasion indicating that all classes of algae were equally affected, including the large colony-forming diatoms that dominated the phytoplankton of the western basin in previous years.

INDEX WORDS: Lake Erie, phytoplankton, zebra mussels.

RUNNING TITLE: Zebra Mussel Impacts on Lake Erie Phytoplankton

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INTRODUCTION

Lake Erie has a well documented history of eutrophication, and the western basin in particular was notorious for dense algal blooms during the 1950s and 1960s (Davis 1968, Beeton 1969). During the 1970s, significant reductions in phosphorus loading to Lake Erie were achieved through (1) legislation reducing the "allowable" levels of phosphates in laundry detergents, and (2) by upgrading sewage treatment plant operation to include chemical precipitation of phosphorus (Phosphorus Management Strategies Task Force, 1980). The resultant reductions in phosphorus loading to Lake Erie were correlated with significant reductions in the phytoplankton in the western basin during the 1970s (Nicholls *et al.* 1977, 1980).

More recently, colonization of Lake Erie by the zebra mussel (Dreissena polymorpha) has provided a potential for further reductions in phytoplankton biomass because of its filter-feeding habit, wide distribution and high densities (Hebert *et al.* 1989, Griffiths *et al.* 1991, Leach 1993). The major expansion of the zebra mussel population in western Lake Erie is believed to have occurred during 1989-1990. Both larvae and adults were observed in the western basin in 1988; however, larval densities increased by more than 10 times between 1988 and 1989 and again between 1989 and 1990 (Wu and Culver 1991, Leach 1993).

This paper reports on long-term chlorophyll and phytoplankton data collected at four nearshore sampling sites in Lake Erie. Changes in phytoplankton were expected in response to declines in phosphorus loading and the recent invasion of zebra mussels. Two upstream "control" sites in southern Lake Huron are included for reference.

METHODS

Samples of "raw" untreated lakewater were collected weekly at each of four municipal water intakes in Lake Erie and two intakes in southern Lake Huron (Fig. 1, Hopkins 1983).

Prior to 1972, phytoplankton samples analyzed by waterworks personnel were concentrated by sand filtration followed by enumeration of phytoplankton taxa in Sedgewick-Rafter chambers using compound microscopes at 200X magnification (A.P.H.A. 1965). After 1972, all samples were concentrated by sedimentation after fixation with Lugol's iodine solution. The concentrated samples were then transfered to 25 mL vials and preserved with formalin for subsequent analysis.

All phytoplankton samples analyzed since 1970 at the Ontario Ministry of the Environment's Rexdale laboratory were concentrated by sedimentation and preserved with Lugol's formalin solution. Since 1976, identifications and enumerations have been made at 300x and 600x magnification using inverted microscopes and Utermöhl-type counting chambers. Phytoplankton densities were expressed as Areal Standard Units/mL (Hopkins and Standke 1992), where one Areal Standard Unit (A.S.U.) is equivalent to an algal cell area of 400 μm^2. Total cell volume and A.S.U. measurements have been shown to be highly correlated (Nicholls 1981).

Phytoplankton analyses have been done at the Rexdale laboratory since 1975 (Elgin), 1981 (Dunnville), 1982 (Union), 1986 (Lambton), 1987 (Grand Bend and Blenheim). Comparisons of the two sample processing techniques revealed that at some locations small flagellates (mainly Chrysophyceae, Prymnesiophyceae and Cryptophyceae, e.g., Chrysochromulina and Rhodomonas spp.) were routinely overlooked by waterworks staff. However, in these diatom-dominated areas of the Great Lakes (Munawar and Munawar 1976), these underestimates of total phytoplankton biomass resulting the from omission of small flagellates are likely insignificant, and we have consequently applied no correction factor.

This paper focuses on the most recent changes in phytoplankton, with data analysis concentrated on the 2-3 year periods preceeding and following the arrival of the zebra mussels in Lake Erie. During this time (1987-present), phytoplankton samples were processed at the Rexdale laboratory using the inverted microscope procedures described above (see Nicholls and Carney 1979 for details). Phytoplankton samples have been collected weekly since the inception of this program; however since 1983, aliquots of each of the monthly samples were combined by month (usually four/month) for analysis. The data we report (since 1983), therefore, represent monthy average phytoplankton density. No weekly results are available after 1982.

Since 1985, samples collected weekly were analyzed for chlorophyll a by filtration through 1.2 μm nylon filters, extraction in 90% acetone (20 min. on a mechanical shaker, followed by standing overnight), spectrophotometric analysis at 710, 750, 630, 645, and 665 nm and calculation of chlorophyll concentration using standardized SCOR-UNESCO equations. Similar methods were used prior to 1985 (Ontario Ministry of the Environment 1981), except that particulate chlorophyll was collected on cellulose nitrate filters with washing and glass fiber filtration prior to spectrophotometry. The nylon filter method has greatly improved precision (<5% standard deviation on replicates) and has increased yields by about 35% (Joan Crowther, Ont. Min. Envir., unpublished report, May 1985). Consequently, all of the original chlorophyll a data for the period 1976-1984 inclusive were adjusted by +35%.

SYSTAT V. 4.0 (Wilkinson 1988) was used to generate Pearson product-moment correlation coefficients from linear regression analyses. The proportional representation by the dominant classes of planktonic algae were examined for the two-year period 1987-1988 (mainly pre-zebra mussels) and for 1989-1990 (post zebra mussels). Significant differences ($\alpha = 0.01$) were tested for by the Chi-squared statistic using the contingency table analysis programme "CTBL" (Texas Instruments T1-74 BASICALC™ calculator). The 95% confidence intervals on predicted values (from a linear regression analysis) were computed according to Sokal and Rohlf (1981, pp.469-477).

RESULTS AND DISCUSSION

Except for the period 1978-1980, there was a well defined long-term downward trend in phytoplankton density in samples from the Union water intake. Between the 1970 and the mid-1980s, total phytoplankton decreased about 80% at this location (Fig. 2). This decline appeared to be confined to the western basin; although relatively high annual averages were also recorded during the mid to late 1970s at the Dunnville location and declined significantly during the 1980s (Fig. 2).

No long term trends could be identified at the upstream reference locations in southern Lake Huron (Fig. 2).

The dramatic decline in the western basin (Union) phytoplankton densities is most logically explained by the coincidental decreases in total phosphorus loading during the past 20 years. Owing mainly to improved sewage treatment and phosphorus removal at the Detroit Metro Wastewater Treatment Plant, the annual total phosphorus loading to the western basin of Lake Erie from the Detroit River declined substantially during the 1970s and early 1980s (Hartig 1983). More recently, other important sources of phosphorus for the western basin of Lake Erie have been brought under control resulting in a decline in the annual total phosphorus input to the western basin of about 50% between 1974 and the late 1980s (Lesht *et al.* 1991, Dolan 1993).

More recently, significant declines in phytoplankton were observed during late 1988 at Union and during 1989 at the other Lake Erie locations (Fig. 3, Table 1). Reductions in total phytoplankton of 92%, 90%, 76% and 62% at Union, Blenheim, Elgin and Dunnville, respectively, between the two-year "pre" zebra mussel (1986-1987) and the two-year "post" invasion period (1989-1990) do not appear to be related to any coincidental further reductions in nutrient loading, but do coincide with the establishment of dense populations of zebra mussels in Lake Erie (Leach 1993).

The significance of the recent declines in total phytoplankton in western Lake Erie was determined by a simple linear regression analysis. On the assumption that phosphorus loading was the most important single factor controlling the annual average density of phytoplankton in the Union intake samples prior to the zebra mussel invasion, a linear regression model was derived for the period 1974 to 1987 inclusive (P loading data are not available prior to 1974 (D. Dolan, pers. comm., Feb. 1993).

$$\text{PHYTO} = 0.557(\text{P Load}) - 2016; \quad (n=14;\ r=0.805)$$

where:

1) PHYTO is annual average phytoplankton density in Areal Standard Units/mL (weekly samples from the Union water system intake), and

2) P load is the total phosphorus loading rate to the western basin from all sources in thousands of metric tons/year.

This model was used to predict the phytoplankton density for 1988, 1989 and 1990 (Fig. 4). The model predicts annual averages of between about 1000 and 2600 A.S.U./mL for each of these years which are considerably higher than the measured average values of 444, 73 and 30 A.S.U./mL for these three years (Fig. 4). It is therefore clear that some factor other than phosphorus load (which we are suggesting is zebra mussel filtration) has contributed to the recent dramatic decline in phytoplankton.

The impacts on phytoplankton were equally dramatic among all taxonomic groups (Table 1, Fig. 5). Chi-squared contingency table tests suggested that the relative distributions of the algal classes were independent (at $\alpha = 0.01$) of the two time periods indicated. Further confirmation of the uniformity of algal class composition before and after the zebra mussel invasion was found in the contingency coefficient (C) calculated for each site. The larger the discrepancy between expected and observed values in a k X r contingency table, the higher the value of C, where $C = \sqrt{\chi^2/(N+\chi^2)}$ (Siegel 1956). For all four Lake Erie sites

(Union, Blenheim, Elgin and Dunnville), C ranged between 0.048 and 0.065 (Table 1) and was not significantly different from zero according to the Chi-squared test ($\alpha = 0.01$).

Because chlorophyll a concentrations were significantly correlated with phytoplankton densities at all four Lake Erie sampling sites ($P<0.05$, Fig. 6), reductions in chlorophyll concentrations between the summers of 1988 and 1989 were also evident (Fig. 7). Chlorophyll a concentrations averaging <1 µg/L in the Union intake samples (western basin) during the April to September period of 1991 are typical of oligotrophic areas of the upper Great Lakes and are in sharp contrast to concentrations in the 10-14 µg/L range recorded in the early 1970s (Fay and Rathke 1980, Glooschenko et al. 1974). Leach (1993) also observed declines in chlorophyll concentrations in Lake Erie which he attributed to zebra mussel water filtration effects. Leach (1993) measured chlorophyll a at a number of sampling locations in the western basin (offshore from the Union intake location) and in the west-central basin (offshore from the Blenheim intake location) during 1988-1990. He showed decreases in average May-November chlorophyll a concentrations of 52% and 30% in the two sampling areas, respectively, between 1988 and 1990, while the intake data showed declines of 69% and 88% over the same time periods. Some of the reason for the apparently higher rate of chlorophyll decline in the intake samples may relate to effects of water filtration by zebra mussels inside the intake structures.

The role of mussels inside the intake structures

Underwater inspections of the intake cribs and the interiors of the intake pipes, including video records, were completed during the spring and fall of 1989, the fall of 1990, and the spring of 1991 at Blenheim, and at Union during the spring and early summer of 1991. In all cases, colonization by zebra mussels was greatest at the mouth of the pipe and on the crib structure itself, where densities of up to 60,000 animals/m^2 were found (contractor reports on file, Ontario Ministry of the Environment, London).

Zebra mussel filtration rate is highly variable depending on body mass, food particle concentration and other factors, but for purposes of scoping an estimate of the zebra mussel filtration potential within the intake pipe itself, an average filtration rate of one litre per animal per day (Reeders and Bij de Vaate 1990) was used along with other necessary physical data as follows: intake length = 460 m; intake diameter = 1.37 m; flow = 0.6 m/s; total volume = 6.8×10^2 m^3; water residence time = 0.21 hours. An estimate of the total number of zebra mussels of 3.8×10^7 was determined from the estimates of areal coverage and density developed by Aquatic Sciences Inc. (1991) for the Union intake during surveys in April and June of 1991. This intake population estimate accounts for the observed progressive decrease in density from the intake crib along the length of the pipe to the water treatment plant.

Using the above data, we calculated a total water volume filtration of 3.3×10^5 l during the 0.21 hour residence time of the lakewater in the pipe. This represents about 50% of the total flow through the pipe for an equivalent time period. In other words, the zebra mussel population in the pipe might be expected to reduce the phytoplankton densities in water entering the pipe by an additional 50% at the sampling point in the plant.

While this estimate serves to indicate the potential effect of the zebra mussel pipe population on the concentrations of suspended algae inside the intake pipe, it is probably an overestimate of the impact. The pipe inspection reports indicated a large number of dead animals in the areas of highest density where layering of the organisms was prevalent. Because no estimate of the numbers of healthy, actively filtering animals was available, our estimate of the total population may greatly exceed the total number of active filter-feeders. The total potential removal of suspended algae within the pipe could therefore be much less than the estimate of 50% calculated above. Some support for this was found in a comparison of the intake findings with those of Leach (1993). The higher percentage decline in the intake samples over the open lake samples resulted from much higher chlorophyll concentrations pre-zebra mussels (1988 data) rather than from greatly depressed post-zebra mussel chlorophyll concentrations. For example, the May to November average chlorophyll a concentration for 1988 in the Union intake samples was 26% higher than the comparable mean at Leach's (1993) western basin sampling stations, while the 1990 intake average was only 18% lower than the main lake average. If a resident pipe population of mussels were the main reason for the decline measured in the intake samples, then a greater percentage reduction would have been expected.

In our view, a more important reason for the more dramatic decline in chlorophyll in the intake water over the main lake relates to the fact that the intake samples were collected from a relatively nearshore habitat with higher initial phytoplankton densities and higher zebra mussel filtration rates than found in offshore water. The lengths of the Union and Blenheim intakes are 460 m and 750 m, respectively. In contrast, Leach's stations in the western basin are 3-20 km offshore and in the west-central basin are about 5-30 km offshore. It is reasonable to expect that the effects of zebra mussel filtration would be greater in shallower nearshore areas in closer proximity to zebra mussel substrate.

Higher in-shore chlorophyll concentrations are a common phenomenon in the Great Lakes (Glooschenko *et al.* 1974, Fay and Rathke 1980). Algae suspended in the surface waters are affected by winds that often result in high concentrations in nearshore areas. For example, the September 1988 average chlorophyll concentration of 20 μg/L in the Blenheim intake samples resulted from a dramatic increase in chlorophyll between the first and second week of sampling and was followed by a steady decline to the end of the month (weekly measurements of 7.1, 39, 22, and 12.3 μg/L). In contrast, the open lake (west central basin) average for the same month was only 4.5 ± 0.5 μg/L (Leach 1993). We suggest therefore, that the high rates of phytoplankton decline measured in the intake samples may be more typical of Lake Erie inshore areas rather than offshore areas, mainly because of higher inshore phytoplankton densities pre-zebra mussels, and because of a more intensive filtration by zebra mussel populations resident in these shallow, nearshore areas. The capacity of zebra mussels to "clear" the water undoubtedly relates directly to the size of the mussel population (higher in nearshore and shoreline areas with suitable substrate) and indirectly to the volume of water available to the animals (lower in shallow, inshore areas).

Zebra mussel dispersal and phytoplankton impacts

D. polymormpha was probably first introduced into Lake St. Clair in the summer of 1985 as veliger larvae in ship ballast water (Hebert *et al.* 1989, Griffiths *et al.* 1991). Adults of the species were first found during the summer of 1988 at several locations in Lake St. Clair at densties of up to 200 individuals/m^2 (Hebert *et al.* 1989). The first year of major successful reproduction is believed to have been 1988 (Hebert *et al.* 1989). Based on subsequent findings of adult zebra mussels along the north shore of Lake Erie, a range extension rate of approximately 250 km/year was calculated (Mackie 1991).

The time lags in the first measured significant decrease in phytoplankton densities at the four Lake Erie sampling locations permitted an indirect estimate of the rate of eastward range extension of zebra mussels along Lake Erie's north shore. A value of 170 km/year was calculated from a highly significant correlation between date of phytoplankton impact and distance from Lake St. Clair ($r^2 = 0.978$).

The leading edge of the eastwardly advancing zebra mussel population was undoubtedly mainly by passive transport of veliger larvae by water currents. Over time and distance, larval densities would be thinned by dilution, predation and other losses. Adult populations ultimately developed from the settling stage of the immature animals in areas of suitable substrate. The intake data show that the first significant effects on phytoplankton lagged behind the pioneering zebra mussel colonies by about one year. For example, adult zebra mussels were first seen in the Port Stanley area of Lake Erie in the fall of 1988 (Mackie 1991), but the major phytoplankton grazing impacts were not measured until the summer of 1989 at our nearby Elgin sampling site. Zebra mussels first appeared on artificial substrates at Port Dover in August of 1989 (Mackie 1991), but again, the first significant impact was measured at our Dunnville sampling site (about 40 km east of Port Dover) in the summer of 1990. It is clear now that the invading "front" in the eastward movement of zebra mussels in Lake Erie consisted of larval stages with minimal relative impact on phytoplankton, even after development of sedentary adult colonies. Only in the following year, after recruitment into the adult population of the first cohort from the original invaders, was significant grazing pressure exerted on the phytoplankton. At all four Lake Erie intake sampling locations, further substantial declines in phytoplankton densities occurred during the year following these initial effects.

By November of 1991, the confirmed areas of zebra mussel colonization in the upper Great Lakes included the St. Clair River, the extreme southern end of Lake Huron, all of Saginaw Bay of Lake Huron, the entire nearshore zone of the lower half of Lake Michigan, as well as numerous other localized sites as far afield as Duluth and Thunder Bay in Lake Superior (New York Sea Grant Extension 1991). These populations likely resulted from more recent transport of adults attached to the hulls of boats originating in Lake St. Clair or Lake Erie. No effects on phytoplankton in the Upper Great Lakes have yet been reported, nor can they be detected in our data, with the possible exception of the 1991 chlorophyll data from the Lambton intake which showed the lowest annual average since analyses began in 1978. Another two of three years of data will be necessary at this location before any conclusions about possible zebra mussel effects in southern Lake Huron can be made.

Phytoplankton declines - a Daphnia or Zebra Mussel Effect?

Recently, Wu and Culver (1991) determined filtering rates of large bodied cladocerans (Daphnia) in the western, central and eastern basins of Lake Erie and applied these rates (after correction for animal length) to population estimates made during the June-August periods of both 1988 and 1989 to derive community grazing rates. Because algal biomass increased in late summer of both years (coinciding with Daphnia declines), Wu and Culver (1991) concluded that the Daphnia grazing effects were more important than the zebra mussel impacts on phytoplankton.

The intake data (e.g., Fig. 3) do not consistently support Wu and Culver's observed seasonal trend in phytoplankton (relatively low early summer levels rising throughout the summer). In contrast to Wu and Culver's finding that the late summer increase in phytoplankton was as significant after as before the zebra mussel invasion, the intake data clearly show a breakdown in all seasonal trends in 1989 and 1990 (Fig. 3). Probably of more significance is the dramatic overall decline in total phytoplankton, including fall and winter periods of typically low cladoceran grazing impacts. In particular, the November phytoplankton densities pre- and post-zebra mussels differed by about two orders of magnitude. The filtration activity of zebra mussels is expected to remain high during seasons with low water temperatures as long as food is available (Reeders and Bij de Vaate 1992).

The proportional decline in all major groups of algae, including both large and small forms, is consistent with the feeding habits of Dreissena. Zebra mussels generally consume all particles in the inflowing siphon stream, including large chain-forming diatoms and even some relatively large zooplankton organisms (Ten Winkel and Davids 1982, MacIsaac *et al.* 1991). Organisms and particles which are unsuitable as food items are processed into pseudofecal pellets bound in a mucous matrix and deposited on the substrate. This feeding habit contrasts with that of large Daphnia species where particles caught by the first set of thoracic legs and rejected on the basis of size and shape are immediately returned to the water by the brushing action of the postabdomen. The known feeding habits of cladocerans cannot therefore account for the dramatic declines in the large colonial Fragilaria, whereas the feeding of Dreissena most certainly would. The large chain-forming diatoms, Tabellaria and especially Fragilaria species, that have historically dominated the western Lake Erie phytoplankton (Nicholls *et al.* 1980, Hartig 1985), and which are too large to be grazed effectively by cladocerans, were among those algal species affected most dramatically. Annual average Fragilaria density in 1987 was 360 A.S.U./mL but only 14 A.S.U./mL in 1989 and <1 A.S.U./mL in 1990. This evidence, when combined with the observed time lag in the Lake Erie phytoplankton response from west to east, points very strongly to a zebra mussel effect rather than to crustacean zooplankton as the reason for the recent dramatic phytoplankton declines in Lake Erie.

CONCLUSIONS

Declines in phytoplankton biomass in Lake Erie's western basin averaging about 5% per year over the period 1970-1985 were related to decreased phosphorus loading to the western basin of about the same magnitude. These effects on phytoplankton were not detected at water supply intake sampling locations in the central and eastern basins of the lake. The recent invasion of the lake by zebra mussels has been associated with a much more dramatic decline of Lake Erie phytoplankton, spatially and temporally. The intake sample results are probably typical of inshore areas of the lake and demonstrate a greater impact of the zebra mussels on phytoplankton than observed in offshore waters. The additional water filtration effects from mussels residing within the intake pipes used for sampling the Lake Erie near-shore environment may be of relative minor importance compared to the in-lake effects. The timing of the phytoplankton response at intake sampling locations along the north shore of the lake is in agreement with the observed eastward colonization rate of the zebra mussel in Lake Erie. The dramatic loss of all phytoplankton taxa including large colonial diatoms has distinguished the zebra mussel impacts from those of endemic size-selective filter-feeding crustacean zooplankters and therefore represents a major new pathway for planktonic primary production in the lake.

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Table 1 Annual phytoplankton density at the four Lake Erie water supply intakes (Areal Standard Units/mL) grouped as two-year means pre and post zebra mussel invasion. The Chi-squared (χ^2) statistic (contingency table analysis) and the contingency coefficient (C) are also shown.

	Cyanophyceae		Dinophyceae + Chrysophyceae[1]		Cryptophyceae		Chlorophyceae		Bacillariophyceae			χ^2_{tab}	
	'87-'88	'89-90	'87-'88	'89-'90	'87-'88	'89-'90	'87-'88	'89-'90	'87-'88	'89-'90	χ^2_{cal}	(df=4)	C
UNION	18	2	14	1	41	5.5	34	2	559	41	2.00	9.49	0.053
BLENHEIM	30	1	17	2	29	3	13	1.3	447	51	1.47	9.49	0.048
ELGIN	12	2	9.5	4	41	9	17	3.5	341	83	1.28	9.49	0.049
DUNNVILLE	13	3.6	17.3	8.5	33	12	22	6	171	71	1.52	9.49	0.065

[1] Averages for Dinophyceae and Chrysophyceae were combined to meet Cochran's (1954) Chi-squared contingency table analysis criterion that no cell have an "expected" value of < 1.

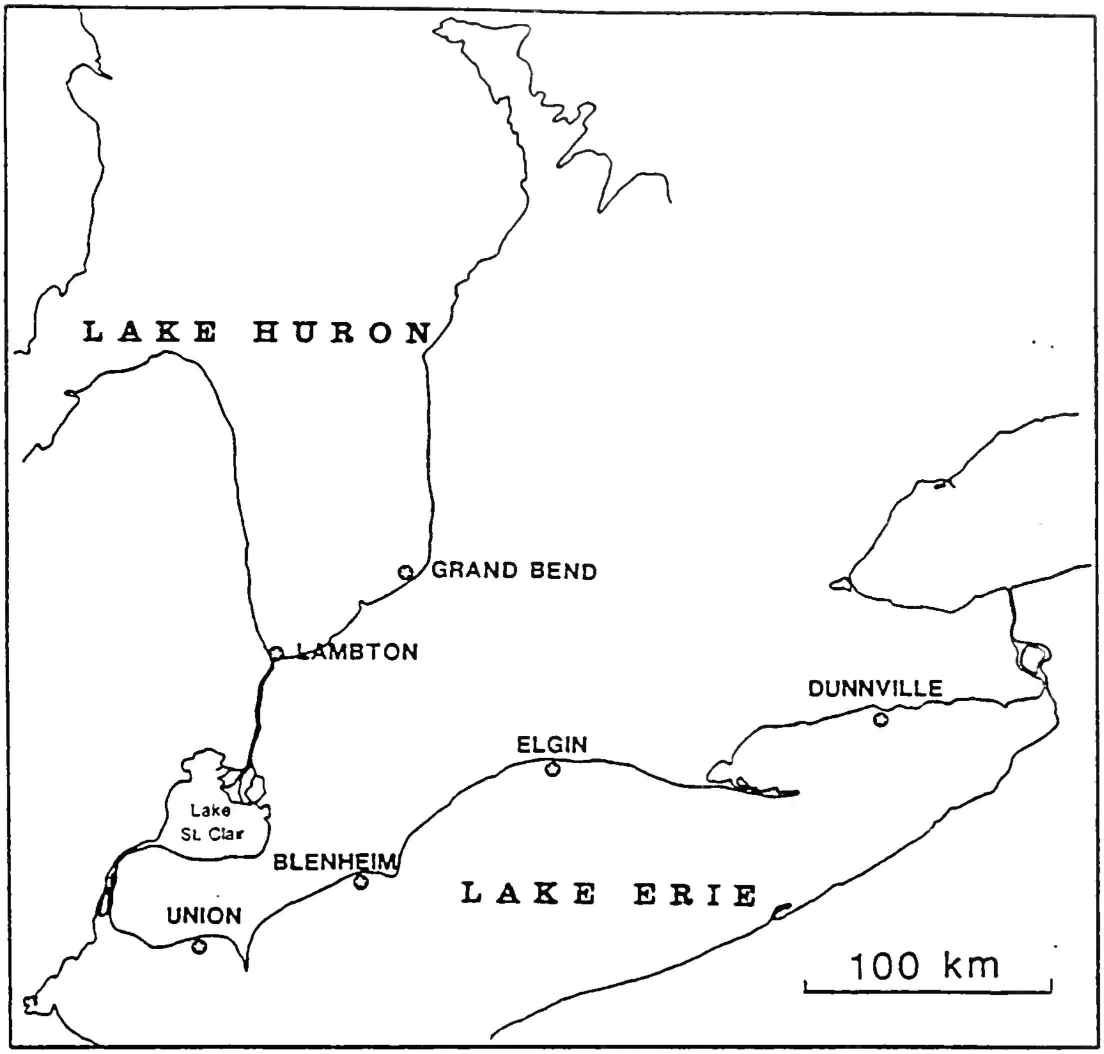

FIG. 1. Map showing the locations of four Lake Erie municipal water treatment plant intakes from which lakewater samples have been collected for nearshore water quality time trend assessments. Also included are two upstream "control" locations in Lake Huron. The lengths and depths of the intakes are as follows: Lake Huron Water Supply System (Grand Bend), 2530m and 8m; Lambton Area Water Supply System (Sarnia), 100m and 12m; Union Area Water System (Kingsville), 460m and 3m; Blenheim Area Water System (Bleinheim), 750m and 13m; Elgin Area Water System (St. Thomas), 1250m and 12m; Dunnville Regional Water Supply (Dunnville), 500m and 6m.

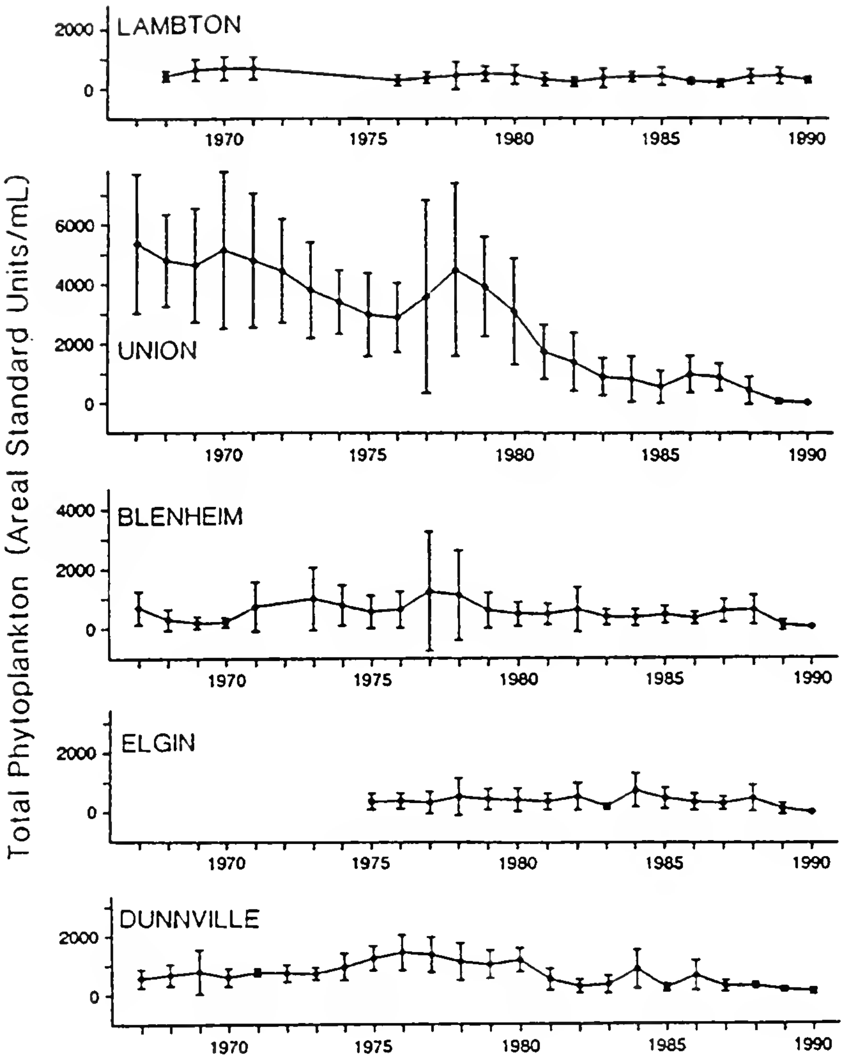

FIG. 2. Phytoplankton densities (annual mean in Areal Standard Units/mL ± 1 St. Dev. calculated from monthly means) at the Lambton location (Lake Huron outflow) and at the four Lake Erie sites, 1967-1990.

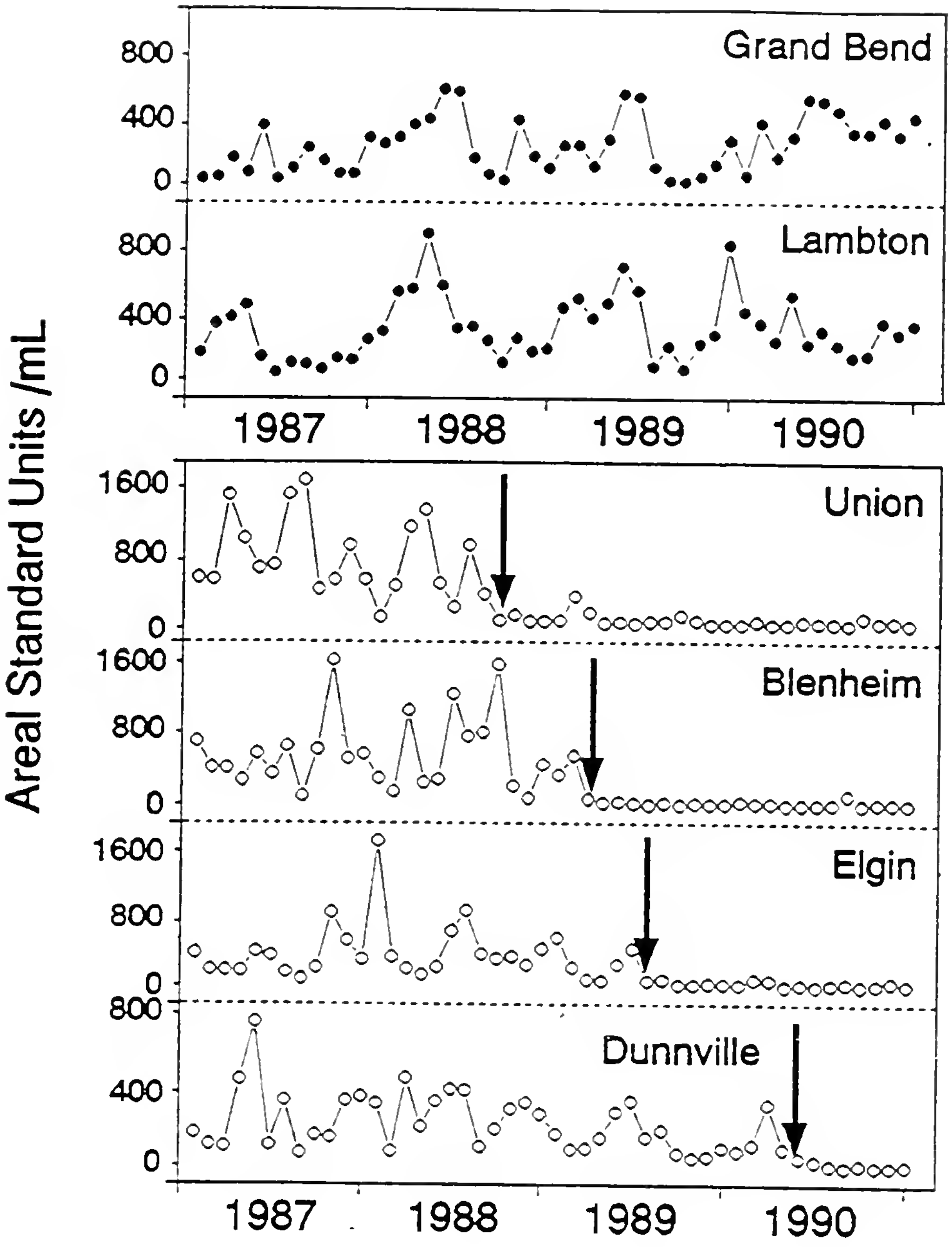

FIG. 3. Phytoplankton densities (Areal Standard Units/mL) at the two Lake Huron (Grand Bend and Lambton) and four Lake Erie sampling locations, 1987-1990. The arrows indicate the apparent beginning of the zebra mussel impact at each location.

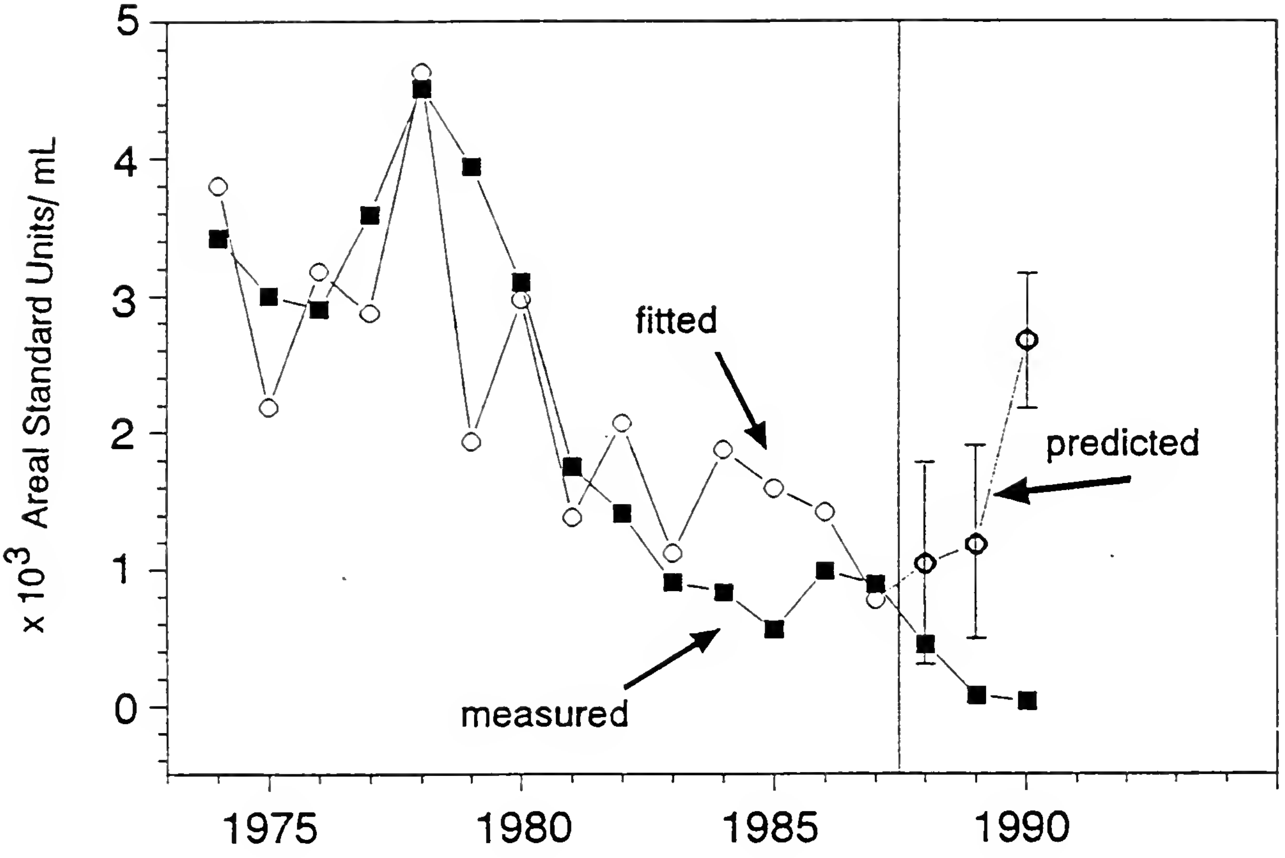

FIG. 4. The measured annual average phytoplankton density in Union intake samples collected weekly compared with the "fitted" values derived from a 1974-1987 linear regression of western basin total phosphorus load on phytoplankton density. Also shown are phytoplankton densities for 1988, 1989 and 1990 with the 95% confidence intervals predicted by this regression equation.

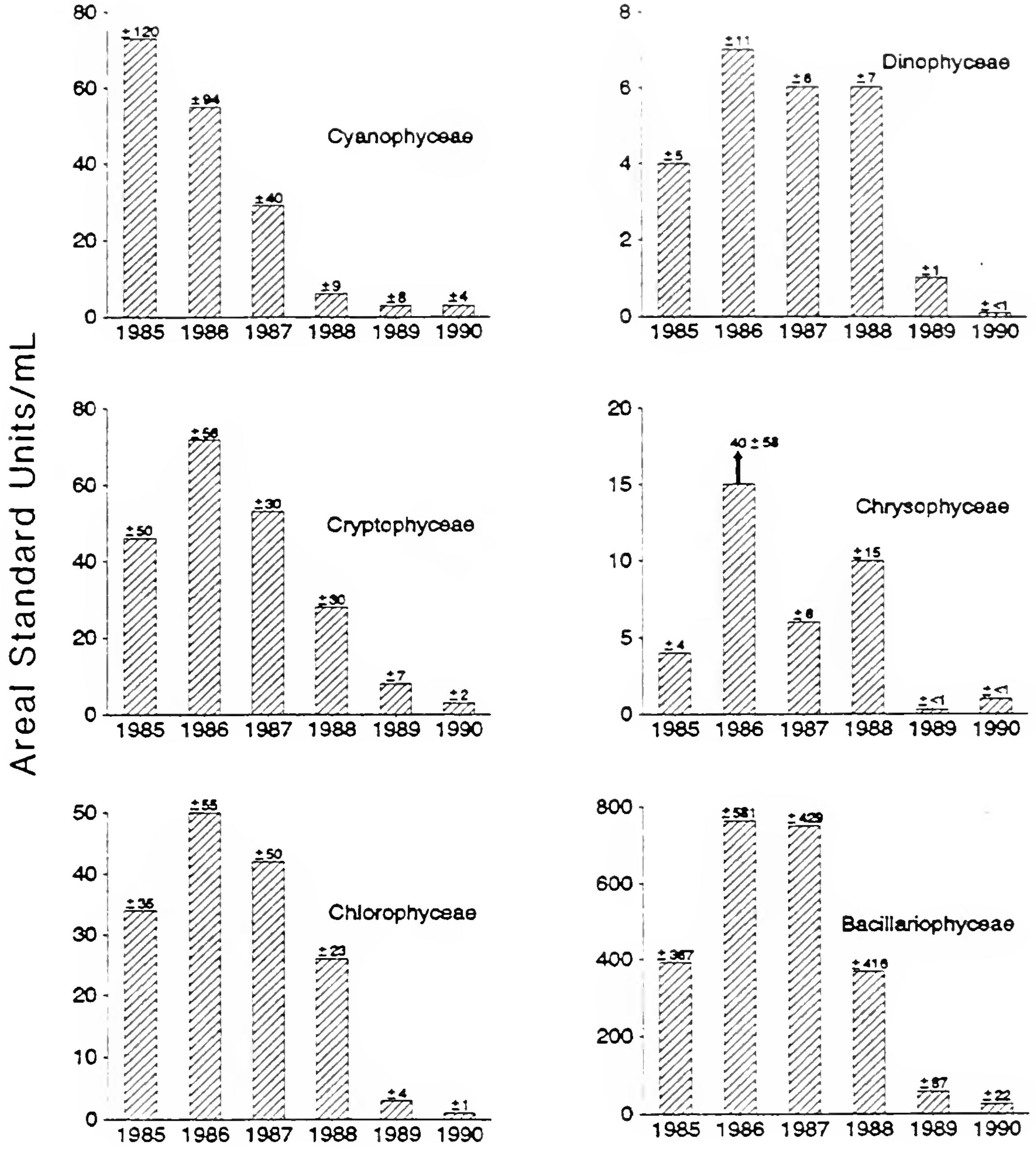

FIG. 5. Annual average densities (±1 St. Dev. indicated at the top of each bar) of the six dominant classes of algae in weekly samples from the Union Water System intake from 1985 to 1990.

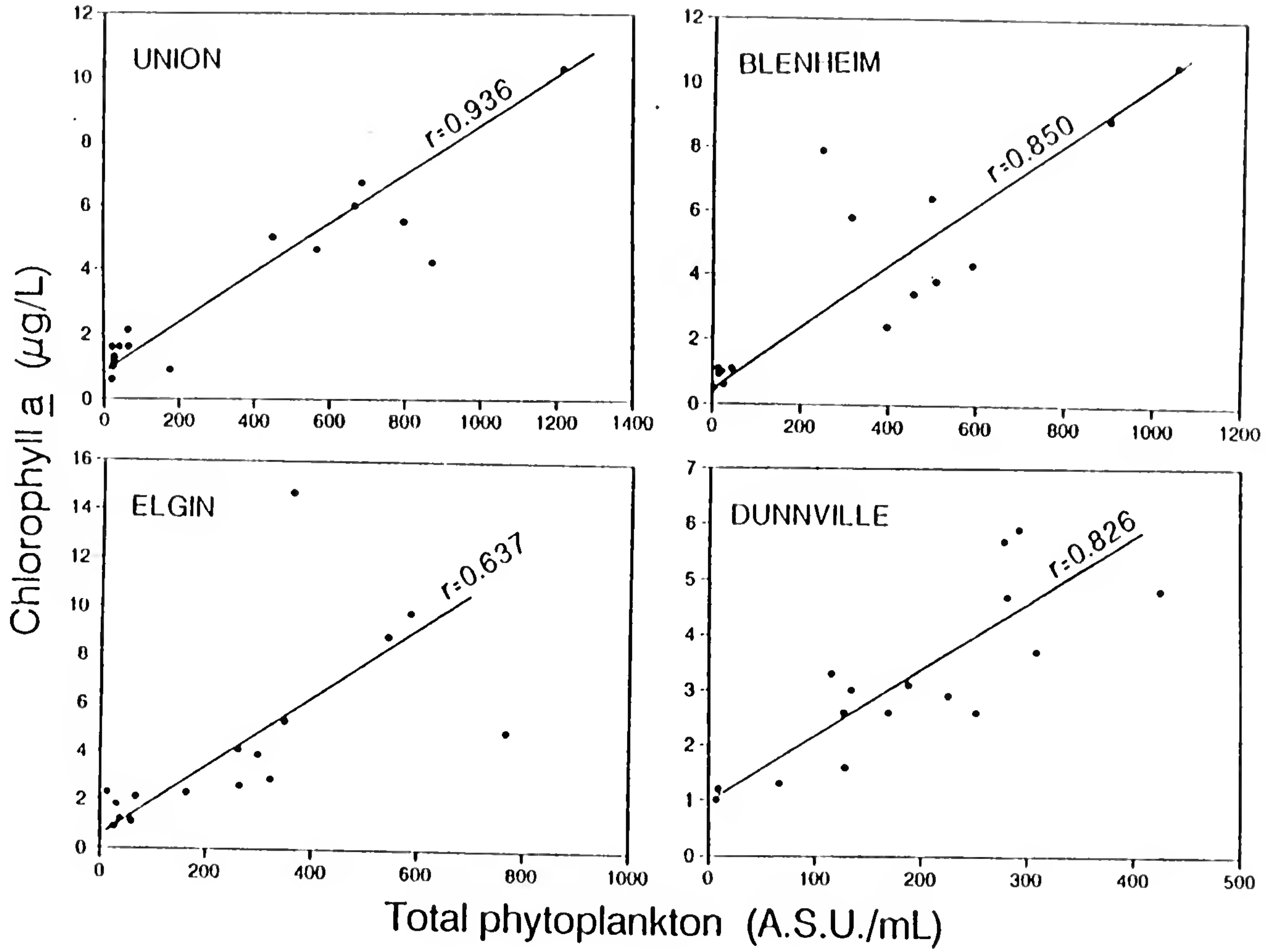

FIG. 6. The relationships between the seasonal mean phytoplankton densities (Areal Standard Units/mL) and chlorophyll a concentrations at the four Lake Erie sites, 1987-1990.

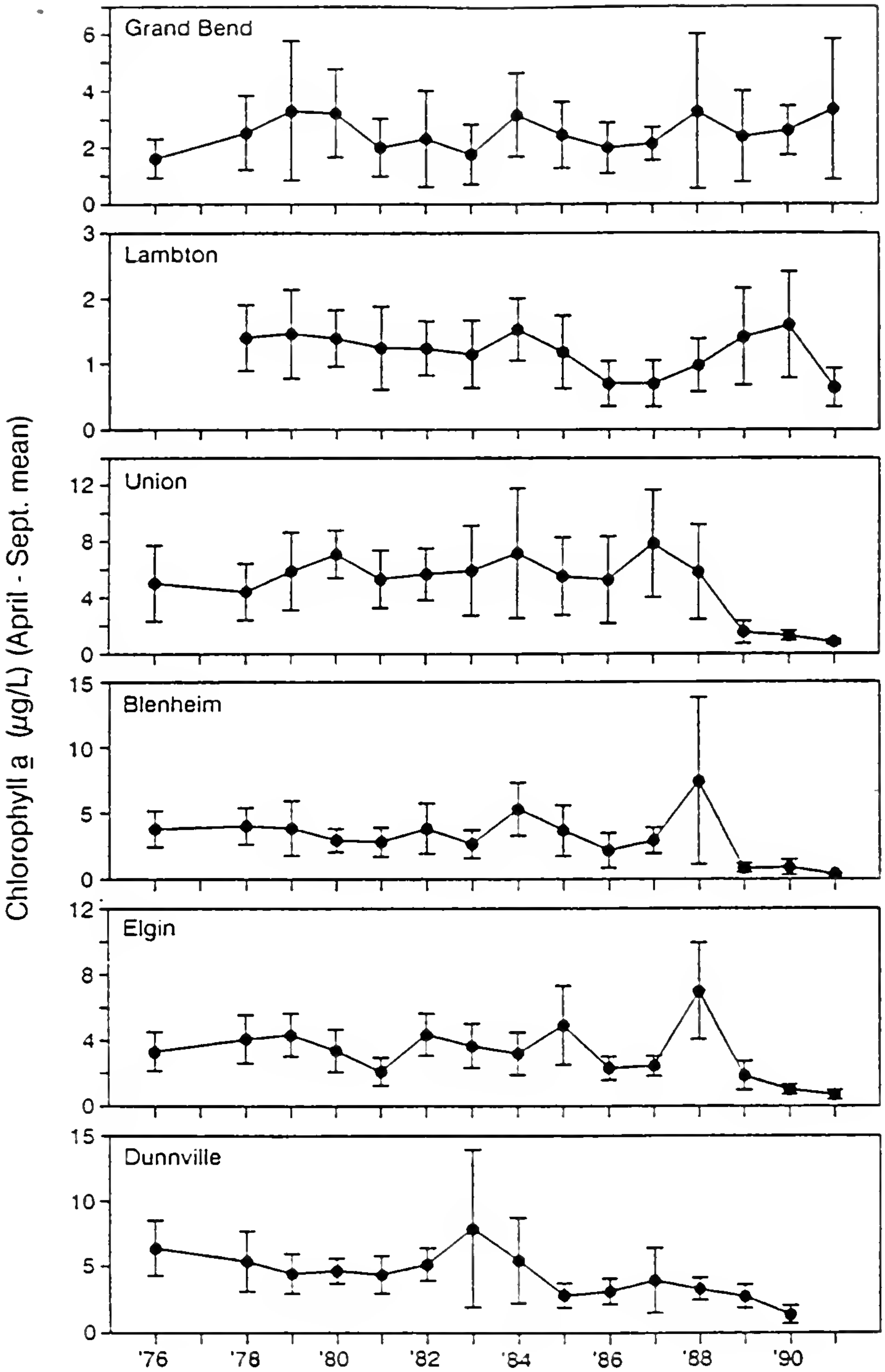

FIG. 7. April through September arithmetic mean chlorophyll a concentrations at two locations in southern Lake Huron (Grand Bend and Lambton) and at four locations in Lake Erie, 1976-1991.